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# EEG Data Collected From Helicopter Pilots in Flight Are Sufficiently Sensitive to Detect Increased Fatigue From Sleep Deprivation

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This investigation determined whether the electroencephalographic (EEG) changes associated with sleep deprivation could be reliably recorded from aviators flying standardized maneuvers in an aircraft. In-flight EEG data were recorded from 10 UH-60 helicopter pilots who were kept awake for approximately 26 hr. In addition, resting EEGs and mood data were collected in the laboratory between flights. Results indicate that EEG theta activity, and to some extent delta activity, increases as a function of sleep deprivation in both settings. In addition, mood decrements were associated with the fatigue from sleep loss. These results indicate it is possible to monitor a pilot's general fatigue levels via the EEG without interfering with the primary duty of flying the aircraft.

The ability to perform in-flight assessments of aviator status could enhance safety by providing an objective indication of performance readiness. If it were possible to quantify when a pilot is suffering from some stressor to the extent that his or her performance is being compromised, timely countermeasures could be implemented to alleviate problems. Unfortunately, it is difficult to accomplish this in the flight environment because of drawbacks associated with traditional testing algorithms. There is need for an approach that (a) can be conducted during the operational task (flight); (b) is feasible from an equipment and personnel perspective; and (c) is objective, reliable, and valid. A measure that might satisfy all

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of these requirements is one that relies on psychophysiological assessments (Caldwell, Lewis, Darling, Dillard, & Johnson, 1994).

Of these, the electroencephalogram (EEG) is the most direct indication of central nervous system (CNS) functioning. Studies have established the sensitivity of EEG activity to stressors such as sleep deprivation. Comperatore et al. (1993), Caldwell, Caldwell, and Crowley (1996), Lorenzo, Ramos, Guevara, and Corsi-Cabrera (1995), Pigeau, Heselgrave, and Angus (1987), and others have shown that EEG delta and theta activity is elevated by sleep loss. Delta and theta are reliably accentuated after 23 to 26 hr of wakefulness, approximately the same time at which both mood and performance are most affected (Caldwell, Smythe, LeDuc, & Caldwell, 2000).

However, the advantages of collecting EEGs to assess CNS and presumably "cognitive" activation are somewhat offset by the disadvantages created by data collection and analysis difficulties, particularly in flight. Despite this, some investigations indicate that usable EEGs can be collected during simulator and aircraft flights. Sem-Jacobsen, Nilseng, Patten, and Eriksen (1959) indicated it is possible to obtain usable eight-channel EEG recordings from both pilots and nonpilots in a T-33 jet during flight. Sem-Jacobsen (1961) later reported that a combination of in-flight EEG analysis and motion pictures is helpful in the selection of pilots for high-performance aircraft. Others have offered evidence of the utility of collecting EEGs during fixed-wing flights (Howitt, Hay, Shergold, & Ferres, 1978; LaFontaine & Medvedeff, 1966; Maulsby, 1966). Furthermore, Caldwell and Lewis (1995) and Caldwell et al. (1997) showed that it is feasible to collect and telemeter EEG data from helicopter pilots.

Although few investigators have related in-flight EEG activity to the readiness or stress levels of aviators, Sterman, Schummer, Dushenko, and Smith (1987) showed that EEG theta increases and EEG alpha decreases as a function of heightened flying demands. Also, central EEG asymmetries are accentuated as a function of increased workload. Wilson and Hankins (1994) reported that EEG theta activity reliably increases during flight segments requiring the highest levels of cognitive processing, whereas theta decreases during the segments relying more on psychomotor coordination.

It has not yet been determined whether in-flight EEG recordings are useful for detecting the influence of other stressors such as pilot fatigue; however, laboratory studies have shown that piloting skills and brain activity are affected by sleep loss (Caldwell et al., 1996; Caldwell et al., 2000). In this investigation, EEGs were collected from sleep-deprived participants while they were flying an aircraft to determine whether the increased theta and reduced alpha (recorded in the laboratory) would occur in flight, particularly while pilots were at the controls. Also, mood data were collected to substantiate that the observed EEG changes were related to fatigue.

## METHOD

### Participants

Ten UH-60 aviators (9 men and 1 woman) served as participants. The average age of the participants was 31.2 years (range = 26–46), and the average flight experience was 1,153 hr (range = 300–5,000).

### Apparatus

Resting (eyes-open/eyes-closed) EEG evaluations were completed both in the laboratory and in the aircraft (while the safety pilot was on the controls). Working EEG evaluations (those done while the pilot was flying) were completed only in flight. In addition to the EEG evaluations, mood was measured between flights in the laboratory.

*EEGs.* In-flight EEG evaluations were conducted using a Cadwell Laboratory Airborne Spectrum 32 (Kennewick, WA) mounted in the rear of the UH-60 helicopter (Sikorsky Aircraft, Scranton, PA) and connected to the aircraft's 28-volt power supply. The Airborne Spectrum, equipped with a 32-channel preamplifier, communicates, via radio, with a ground-based Cadwell Spectrum 32 containing specialized communications hardware. Laboratory EEG evaluations were made with a standard Cadwell Spectrum 32. The low filter was set at 0.53 Hz, the high filter was set at 100 Hz, and the 60-Hz notch filter was engaged. Grass E5SH silver electrodes (Quincy, MA) were used to detect EEG.

*Mood assessments.* In the laboratory, mood evaluations were made with the Profile of Mood States (POMS; McNair, Lorr, & Droppleman, 1981). The POMS is a 65-item test that measures affect or mood on six scales: tension–anxiety, depression–dejection, anger–hostility, vigor–activity, fatigue–inertia, and confusion–bewilderment.

### Procedure

Participants completed three training sessions on the first day of their participation. In addition, each participant completed three testing sessions that began on the second day of participation and ended on the morning of the third day. On the training day, participants arrived at the laboratory at approximately 1000 and were released by approximately 2200. On the following day, participants reported to the laboratory at 1700 and remained there (except for the flights) until 1200 the next day. Thus, participants spent only one night at the laboratory but were not permitted to sleep during this time. A flight surgeon conducted a medical records review prior to participation to ensure that each aviator possessed a current up-slip (Department of the Army Form 4186) and that the aviator was free from medical conditions or medications that would have affected fitness for the study.

*Training.* On the training day, participants completed training flights in the laboratory's specially instrumented UH-60 helicopter under the supervision of a safety pilot. Training flights were scheduled for 1400, 1700, and 2000; however, there were occasional delays due to weather or aircraft problems (precise timing was not crucial because the objective was to familiarize participants with the flight maneuvers prior to the test flights). Between training flights, participants completed the POMS.

*Testing.* On the testing day, participants were asked to wake up between 0600 and 0700 and to avoid napping prior to arriving at the laboratory at 1700 for electrode application. In addition, the volunteers were cautioned to avoid caffeine (however, no records were maintained regarding typical caffeine consumption). Once an individual arrived at the laboratory for testing, 25 electrodes were placed on the scalp with collodion in accordance with the International 10-20 system (Jasper, 1958), adding Fpz and Oz. Impedances were reduced to less than 5,000 ohms. The participant was then connected to the ground-based Spectrum 32 and instructed to sit quietly for 5 min with eyes open and then for 5 min with eyes closed. Prior to initiating data storage for the initial EEG, a staff member counseled the participant on how to relax and minimize movements that would have contaminated the EEG record. Following EEG testing, the participant completed one POMS. Afterward, the participant completed another resting EEG and POMS.

After completion of laboratory testing, the participant was driven to Cairns Army Airfield, where the aircraft departed at 2300 for the first 1.5-hr flight. After reaching altitude, with the safety pilot at the controls, the participant completed an eyes-open/eyes-closed EEG (10 min total). Afterward, the safety pilot transferred control of the aircraft to the participant, who completed a climb, a descent, two right and two left standard-rate turns, a right descending turn, a left climbing turn, six straight-and-level maneuvers, and an instrument landing system approach (there were 15 maneuver segments). If participant-generated muscle or movement artifacts were present, the maneuver was stopped until the quality of the signal was sufficiently "clean" to continue.

At the conclusion of the flight, the participant was driven back to the laboratory. The next laboratory test session (EEG, POMS, EEG, and POMS) began at 0200. Following this session, the participant departed for Cairns for the second flight (at approximately 0400). After this flight there was one final laboratory test session at 0700 and one final flight at 0900. Afterward the participant was released.

### Data Analysis

EEG data were analyzed by (a) scanning the record for each eyes-open, eyes-closed, and maneuver segment to develop an appreciation for the characteristics of the particular EEG segment; (b) selecting three representative 2.5-sec epochs from each segment; and (c) subjecting the epochs to fast Fourier/power spectral analyses utilizing resident Spectrum 32 software. This procedure yielded data for each EEG segment classified into the four activity bands of delta (1.5–3.0 Hz), theta (3.0–8.0 Hz), alpha (8.0–13.0 Hz), and beta (13.0–20 Hz).

Factor scores for each POMS scale were calculated by the computer on which the POMS was given. The scores were downloaded to another computer for statistical analysis.

## RESULTS

### EEG Laboratory Data

In the laboratory, only resting eyes-open/eyes-closed EEGs were collected at each of the testing periods prior to the flights. There were two assessments within each period. Data were analyzed in two-way analyses of variance (ANOVAs) for session (2045, 2140, 0145, 0240, 0645, and 0740) and eyes (eyes open and eyes closed). The results for only Fz, Cz, and Pz are detailed here.

*Delta activity.* There were session main effects at Fz, $F(5, 45) = 4.41$, $p = .0023$; Cz, $F(5, 45) = 4.93$, $p = .0011$, and Pz, $F(5, 45) = 5.14$, $p = .0008$; and eyes main effects at Fz, $F(1, 9) = 8.31$, $p = .0181$; Cz, $F(1, 9) = 11.25$, $p = .0085$; and Pz, $F(1, 9) = 21.13$, $p = .0013$. In addition, there were Session × Eyes interactions at Cz, $F(5, 45) = 3.30$, $p = .0126$, and Pz, $F(5, 45) = 4.31$, $p = .0028$. There were significant linear trends (shown in Figure 1, top left) at each of the three electrodes due to increases in delta power from 2045 to 0740 ($p < .05$). Also, there was a quadratic trend at Pz because of a sharp increase in delta power at the final two testing times in comparison with the previous four ($p < .05$). The eyes main effects were due to increased delta activity from eyes-open to eyes-closed. The Session × Eyes interaction at Cz was because of a small increase in delta from eyes-open to eyes-closed early in the deprivation period (at 2045), followed by a much larger increase later at 0645 ($p < .05$) with a similar tendency at 0740 ($p = .066$); however, there were no significant differences in the middle. A similar pattern occurred at Pz, with the exception that the early difference was seen at 2140 and the later differences were observed at 0645 and 0740 ($p < .05$). These interactions are shown in Figure 1 (top right and bottom).

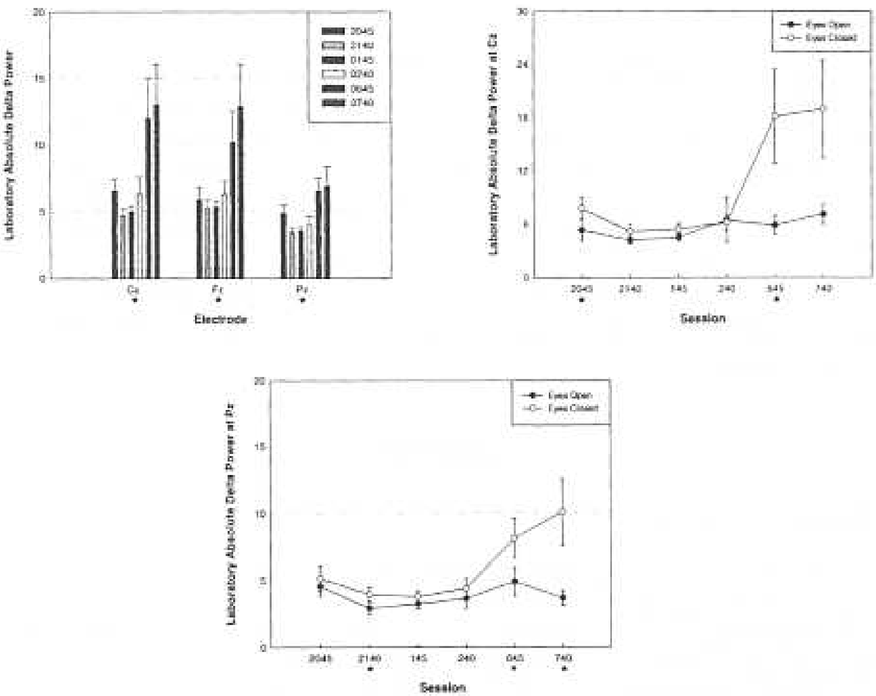


FIGURE 1 The effects of sleep deprivation and eyes-open/eyes-closed (for Cz and Pz) on EEG delta activity collected in the laboratory. (Significant effects denoted by asterisk.)

*Theta activity.* There were significant main effects and interactions at all three electrodes. The session main effects at Fz, $F(5, 45) = 10.77$, $p < .0001$; Cz, $F(5, 45) = 8.06$, $p < .0001$; and Pz, $F(5, 45) = 6.19$, $p = .0002$, were all primarily due to linear increases in theta activity from the first to the last sessions of the deprivation cycle. However, there was also a single significant cubic trend at Pz and one quartic trend at Fz (see Figure 2, top left). The eyes main effects at Fz, $F(1, 9) = 29.83$, $p = .0004$; Cz, $F(1, 9) = 17.51$, $p = .0024$; and Pz, $F(1, 9) = 25.85$, $p = .0007$, were because the amount of theta at eyes-open was smaller than the amount at eyes-closed. The Session × Eyes interactions at Fz, $F(5, 45) = 3.68$, $p = .0071$; Cz, $F(5, 45) = 4.26$, $p = .0029$; and Pz, $F(5, 45) = 2.92$, $p = .0228$, were all because of more theta under eyes-closed than eyes-open at various points in the deprivation cycle (particularly at 2045, 0145, 0645 and 0740). These interactions are illustrated in Figure 2 (top right, bottom left, and bottom right, respectively).

*Alpha activity.* There were session main effects at Fz, $F(5, 45) = 2.93$, $p = .0226$; Cz, $F(5, 45) = 3.35$, $p = .0117$; and Pz, $F(5, 45) = 3.44$, $p = .0103$; eyes main effects at Fz, $F(1, 9) = 12.49$, $p = .0064$; Cz, $F(1, 9) = 9.36$, $p = .0136$; and

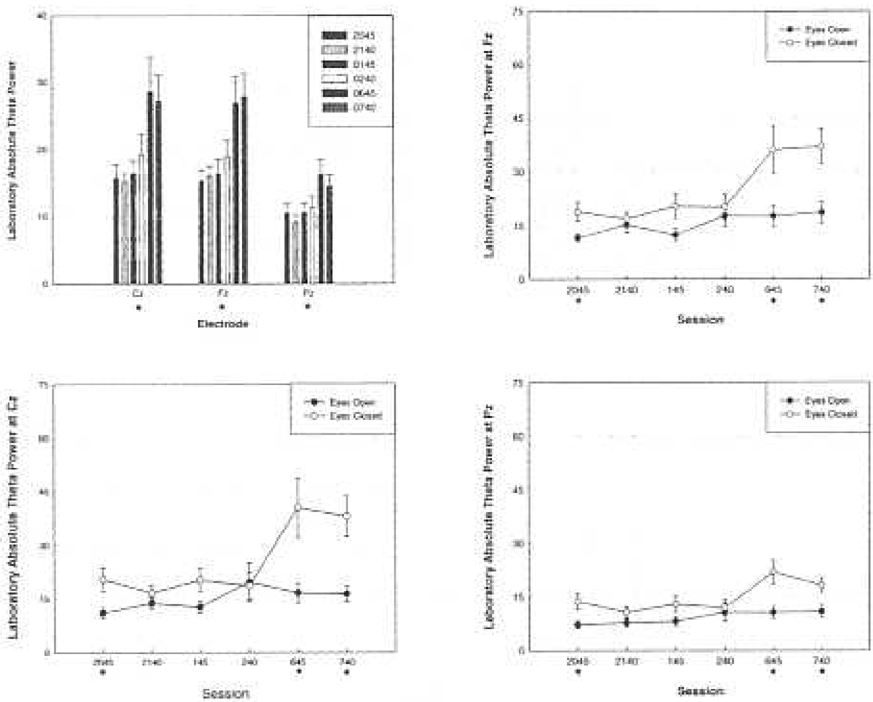


FIGURE 2 The effects of sleep deprivation and eyes-open/eyes-closed (for the midline electrodes) on EEG theta activity collected in the laboratory. (Significant effects denoted by asterisk.)

Pz, $F(5, 45) = 10.34$, $p = .0106$; and Session × Eyes interactions at Fz, $F(5, 45) = 3.47$, $p = .0098$; and Cz, $F(5, 45) = 2.61$, $p = .0371$. Trend analysis showed a linear component in the effects at Cz and Pz (and marginally at Fz) attributable to a decrease in alpha activity from the first to the last part of the deprivation period. However, there was also a cubic component (significant only at Cz and Pz), depicted in Figure 3, top left. The eyes main effects were because alpha was higher under eyes-closed than eyes-open at all three electrodes. The Session × Eyes interactions at Fz and Cz were essentially the result of large differences between the eyes-open and eyes-closed conditions at 2045, 2140, 0145, and 0740, with smaller or more variable differences at 0240 and particularly at 0645 (there was no significant difference between the two conditions for Fz at 0240 or for Cz at 0645). These interactions are depicted in Figure 3 (top right and bottom).

*Beta activity.* There was a session effect only at Pz, $F(5, 45) = 2.44$, $p = .0488$, due to a significant cubic trend ($p < .05$). Beta was relatively high during the first part of the deprivation period (from 2045–0145) in comparison to later

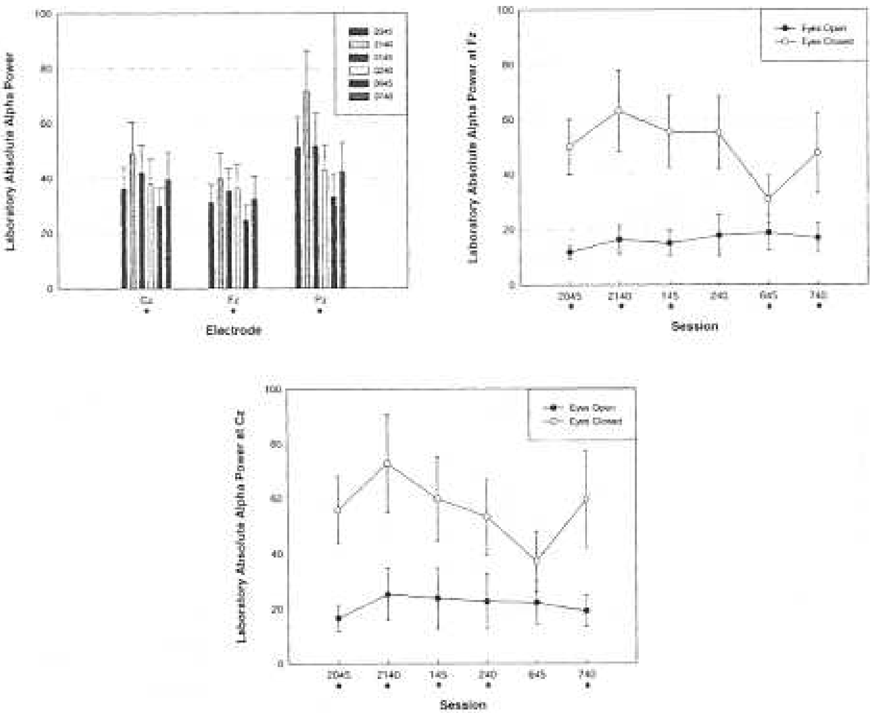


FIGURE 3 The effects of sleep deprivation and eyes-open/eyes-closed on EEG alpha activity collected in the laboratory. (Significant effects denoted by asterisk.)

at 0645 (see Figure 4). However, after 0645, beta activity returned to its previous levels by the last testing time (at 0740). In addition, there were eyes main effects at Fz, $F(1, 9) = 6.90$, $p = .0275$; Cz, $F(1, 9) = 11.34$, $p = .0083$; and Pz, $F(1, 9) = 19.34$, $p = .0017$, all of which were due to greater amounts of beta under eyes-closed than eyes-open. There were no significant interactions.

## EEG In-Flight Data

In the aircraft, EEG data were collected under a resting eyes-open condition at the beginning of each flight (with the safety pilot on the controls) and subsequently during each of the 15 maneuver segments (with the participant on the controls). Data were analyzed in two-way ANOVAs for flight (2300, 0400, and 0900) and segment (resting, Maneuver 1 through Maneuver 15). Only the results for Fz, Cz, and Pz are detailed here. For the sake of brevity, only flight-related differences receive emphasis because EEG changes across flight segments are presumably not relevant to measuring changes in pilot fatigue levels.

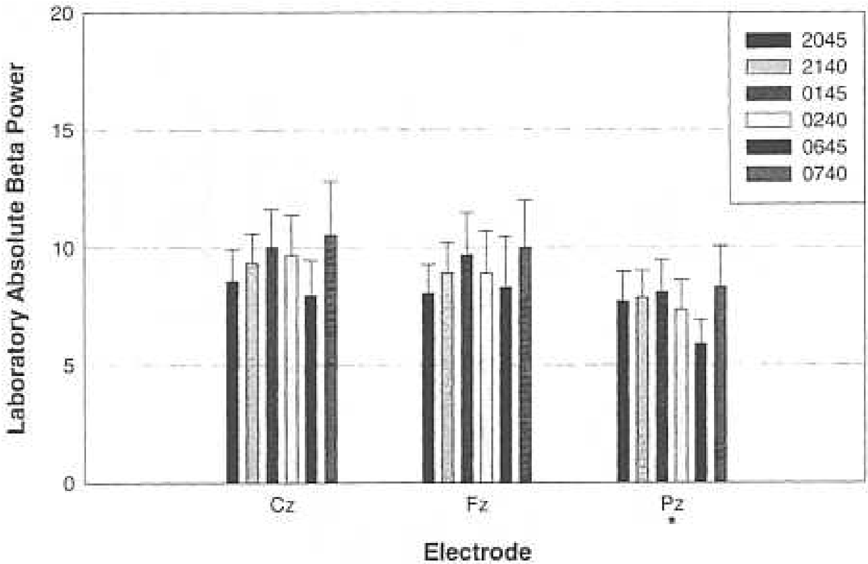


FIGURE 4 The effects of sleep deprivation on EEG beta activity collected in the laboratory. (Significant effects denoted by asterisk.)

*Delta activity.* There was a flight-related difference only at Pz, $F(2, 18) = 3.96$, $p = .0376$, due to the absence of a change from the first to the second flight, whereas delta increased substantially by the time of the third flight ($p < .05$). The means for Fz, Cz, and Pz are shown in Figure 5 (top left).

*Theta activity.* There were significant flight main effects at Fz, $F(2, 18) = 4.56$, $p = .0251$; Cz, $F(2, 18) = 15.92$, $p = .0001$; and Pz, $F(2, 18) = 14.61$, $p = .0002$, all of which occurred because theta increased linearly from the first to the last flight ($p < .05$). At Pz, there was also a significant quadratic trend because there was little difference in the amount of Pz theta in the first and second flights, whereas an increase occurred by the time of the third flight ($p < .05$; see Figure 5, top right).

*Alpha activity.* Significant flight main effects occurred at Cz, $F(2, 18) = 5.29$, $p = .0156$, and Pz, $F(2, 18) = 6.25$, $p = .0087$, but not at Fz. These were due to significant linear trends ($p < .05$) that resulted from increased alpha power from the 2300 flight to the 0900 flight (see bottom of Figure 5).

*Beta activity.* There were no flight main effects in beta activity. This EEG band was not sensitive to pilot fatigue.

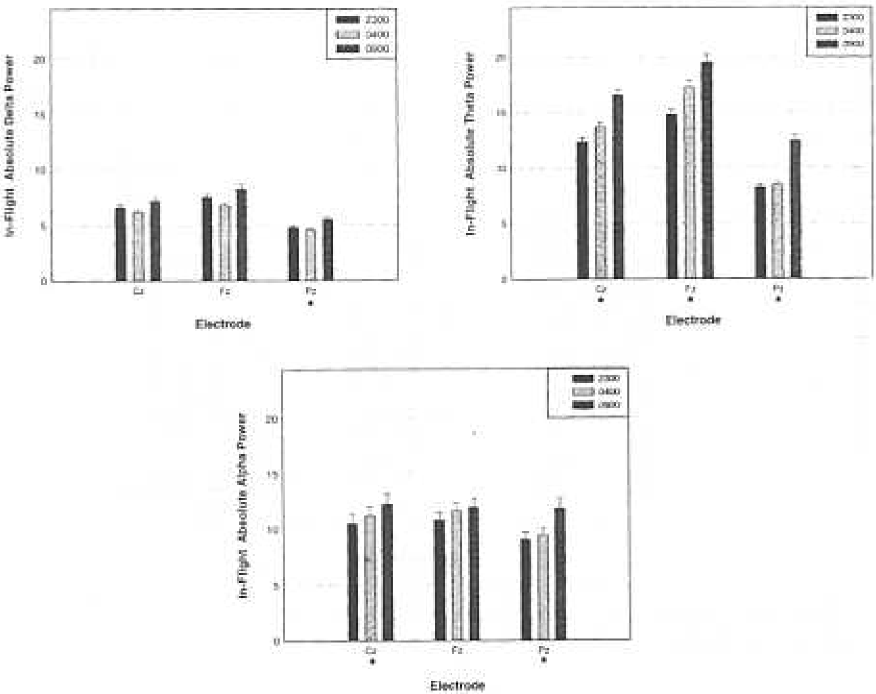


FIGURE 5 The effects of sleep deprivation on in-flight EEG delta activity (top left), theta activity (top right), and alpha activity (bottom) recorded from Fz, Cz, and Pz. (Significant effects denoted by asterisk.)

## POMS

Scores from the POMS were analyzed with one-way ANOVAs on the session factor (2100, 2155, 0200, 0255, 0700, and 0755 in the laboratory) The anger–hostility subscale was dropped because there were no nonzero responses. There were significant main effects on tension–anxiety, $F(5, 45) = 6.31$, $p = .0002$; vigor–activity, $F(5, 45) = 29.67$, $p < .0001$; fatigue–inertia, $F(5, 45) = 27.04$, $p < .0001$; and confusion–bewilderment, $F(5, 45) = 13.04$, $p < .0001$. Mood deteriorated as the hours of continuous wakefulness increased ($p < .01$). As Figure 6 shows, subjective reports of tension, fatigue, and confusion increased from 2100 to 0755, whereas vigor ratings decreased. There were no effects on the depression scale.

## DISCUSSION

The primary purpose of this investigation was to determine whether the fatigue-related EEG changes found in earlier studies during laboratory testing (Caldwell

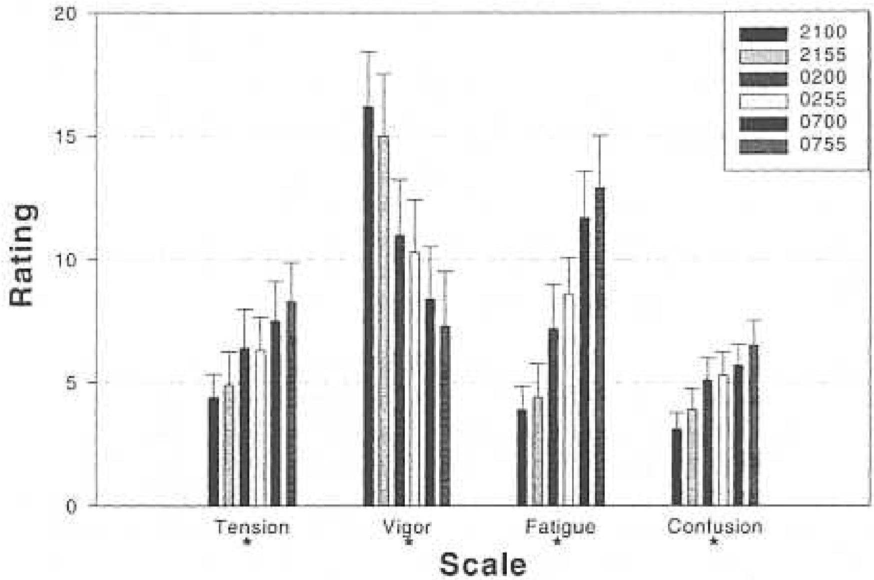


FIGURE 6 The significant impact of sleep loss on subjective ratings from the tension–anxiety, vigor–activity, fatigue–inertia, and confusion–bewilderment scales of the POMS. (Significant effects denoted by asterisk.)

et al., 1996; Caldwell et al., 2000) could be detected in flight. Of particular interest was whether fatigue-related accentuations in EEG theta (3.0–8.0 Hz) activity could be recorded from fatigued pilots because sleepiness and fatigue are known to elevate slow-wave brain activity (Pigeau et al., 1987). Increased theta activity has been associated with generalized performance decrements on cognitive tasks (Belyavin & Wright, 1987) and reduced speed of response to incoming stimuli (Ogilvie & Simons, 1992).

This study in fact revealed EEG effects both in the laboratory and in flight and consistent effects in the EEG theta band across the two settings. Midline theta activity progressively increased from the beginning to the end of the deprivation period, suggesting that fatigue from sleep loss was exerting a negative impact on the alertness of the pilots. In addition, lower frequency delta (1.5–3.0 Hz) activity was also accentuated as a function of sleep deprivation in both testing situations, but the effect was observed only at Pz in the aircraft, whereas it occurred at all three recording sites in the laboratory. Increased delta activity is primarily associated with sleep in normal adults (Ray, 1990).

Differences in alpha activity also occurred in the laboratory and in flight, but the pattern did not show the consistency that was apparent with delta and theta.

In fact, alpha power progressively decreased in the laboratory setting whereas it increased in the aircraft. Such a disparity may have resulted from the more soporific nature of the laboratory environment versus the in-flight environment. Thus, in the laboratory, participants were more likely to actually drift into stage 1 sleep, whereas falling asleep on the controls in flight was less likely to occur because of heightened arousal levels (Billings, Gerke, & Wick, 1975). Despite a lack of consistency in alpha, the effects in both delta and theta strongly suggest that (a) participants were becoming more fatigued as the deprivation period progressed and (b) this increase in fatigue was detectable via EEG recordings both in the more traditional laboratory setting and in the less well-researched aircraft setting.

The mood data collected in the laboratory (prior to each of the in-flight sessions) provide further evidence for a progressive increase in fatigue from the beginning to the end of the sleep-deprivation period. POMS scores indicated that the pilots' ratings of fatigue, tension, and confusion all increased significantly as a function of prolonged wakefulness, whereas ratings of vigor decreased. These findings are generally consistent with reports from earlier studies in which sleep deprivation was a factor (Caldwell & Caldwell, 1997, 1998; Caldwell et al., 2000; Newhouse et al., 1989). In each of these studies, mood effects coincided with performance losses.

In conclusion, the data reported here suggest it is feasible to monitor overall increases in the fatigue of pilots via the acquisition of EEG activity from the in-flight environment. Thus, it is possible to gain insight into the status of aviators without disrupting performance on the primary task of flying. Future studies are needed to establish whether there are correlations between in-flight physiological changes and in-flight performance changes. Also, the collection of mood data in both the aircraft environment and the laboratory would permit the correlation of these data with the EEG results.

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